

An Optimization Technique to Resolve Real-Time Monitoring Using IoT for Smart Energy Meter

J.B. Singh¹, Gaurav Rai^{2*}

Abstract

This paper presents an Internet of Things (IoT)-based smart energy meter designed for accurate, real-time monitoring of household and industrial electrical consumption. Customers and system operators can view real-time patterns of energy consumption with an easy-to-use web-based dashboard. Users can obtain important insights into their electricity consumption through graphical representations and historical data analysis, allowing for more efficient load management, energy conservation, and cost optimization. Users can obtain energy data from any location with internet connectivity thanks to the system's support for remote monitoring. By giving end users comprehensive and easily accessible information, the suggested smart energy meter improves energy use transparency. Additionally, it supports the shift to intelligent energy management systems by enhancing energy efficiency and facilitating informed decision-making. The design, which makes use of IoT technology, is a major step toward the modernization of smart grids and sustainable energy management systems. It also marks a substantial improvement in smart metering infrastructure. The system integrates a microcontroller, current and voltage sensors, and Wi-Fi communication to collect and transmit energy data to a cloud server. A user-friendly dashboard allows consumers to visualize energy usage patterns, enabling better load management and cost optimization. The proposed design enhances transparency, supports remote monitoring, and represents a significant step toward smart grid modernization.

Keywords: Cloud dashboard, IoT, real-time monitoring, smart energy meter, smart grid

INTRODUCTION

Traditional energy meters are unable to provide real-time consumption information, thereby limiting customer awareness and effective energy management. Real-time data collection and cloud-based monitoring for home energy systems are now possible because of the development of Internet of Things (IoT) technology. The IoT has experienced explosive growth and radically changed how devices communicate, control, and manage resources. One of the most important IoT

applications is energy management, as smart systems are essential for efficiently tracking, controlling, and enhancing energy use [22–25]. Customers and utility suppliers face several problems as a result of the growing demand for power and its rising prices, including energy waste, inaccurate invoices, and insufficient real-time monitoring. Conventional energy meters only record total use and require human reading; they do not enable remote monitoring or rapid assessments. Consequently, consumers find it challenging to monitor their daily energy usage and identify

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unusual patterns.

Background

Over the past few decades, energy monitoring systems have changed significantly, evolving from conventional electromechanical meters that could only record basic consumption to contemporary digital smart meters that can perform sophisticated measurement and communication tasks. Conventional energy meters are being replaced with intelligent, networked devices that provide real-time data collection, bidirectional communication, and smooth remote accessibility owing to the explosive expansion of the IoT. These developments have enabled customers, utility companies, and grid operators to estimate energy demand, identify anomalies, continually monitor consumption trends, and optimize total energy usage [1–5]. An effective and automated ecosystem for energy management is created by IoT-based smart energy meters, which include sensors, microcontrollers, wireless communication modules, and cloud platforms [6–8]. By providing users with immediate access to consumption information via mobile or web interfaces, they not only increase billing accuracy and transparency but also raise consumer awareness [9–12]. IoT-enabled smart meters are becoming a vital solution for efficient load control, demand response, and energy waste reduction, as global energy needs continue to climb, and sustainability has become a top priority. Modern smart grids are built on this advancement in monitoring technology, which also facilitates the shift to more intelligent, robust, and efficient electricity distribution networks [13–16].

Problem Statement

Conventional energy meters offer only cumulative data; they are unable to monitor electricity use in real time, identify abnormal usage, or facilitate remote monitoring. This restriction makes it more difficult for customers to comprehend how they use energy and prevents utility companies from quickly detecting problems, energy theft, or load swings. Errors, delays, and inefficiencies in invoicing are further introduced by manual meter reading [17–21]. An intelligent, automated, and networked system that can track usage in real time, deliver precise data, and facilitate predictive analysis for improved energy management is becoming increasingly necessary as energy demand continues to rise. To overcome these specific constraints and effectively increase user awareness and grid efficiency, an IoT-based smart energy meter is necessary. It enables continuous monitoring, bidirectional communication, and timely insights.

Contribution

By combining wireless connection, cloud-based data analytics, and real-time monitoring, this research presents an IoT-based smart energy meter system that improves conventional metering. Users can access comprehensive usage data through a mobile or online interface. Technology allows for continuous power consumption surveillance with greater accuracy and transparency. In contrast to traditional meters, the proposed system provides automatic data logging, anomaly detection, and immediate warnings to assist in identifying anomalous loads, potential defects, or energy waste. The project also provides predictive analysis to help with improved energy planning and offers scalable architecture that can be developed for multi-household or industrial applications. By using effective IoT protocols with inexpensive hardware components, the innovative approach shows how to assist smart grid objectives while updating the energy monitoring process in an economical and useful manner.

RELATED WORK

IoT-enabled smart energy monitoring frameworks have been the subject of research studies in recent years that aim to address the shortcomings of conventional metering systems. Previous studies have shown how communication technologies, including Wi-Fi, GSM, LoRa, and Zigbee, may improve anomaly detection, load forecasting, real-time data collection, and prepaid billing. These smart energy meters allow ongoing monitoring and analytics by integrating sensor modules with

cloud platforms. However, there is still an opportunity to develop better architectural and methodological methods because many suggested systems have issues with accuracy, scalability, data latency, and system cost.

Existing Research

Previous IoT-based energy monitoring models largely relied on bulky hardware units, single-board computers, or isolated communication modules, thereby limiting the overall system efficiency. Many earlier designs offered only basic consumption tracking without real-time feedback or integrated visualization dashboards. Furthermore, low-resolution sensors frequently limited measurement accuracy, and the use of power-intensive modules or expensive network services increased operating expenses. Although some studies introduced prepaid mechanisms or predictive analytics, most lacked seamless integration with cloud databases and mobile applications, thereby reducing their usability in practical home or industrial environments. These drawbacks emphasize the need for a portable, inexpensive, highly accurate energy monitoring system with reliable real-time communication (Figure 1).

Preliminaries

Sensing sensors, embedded controllers, and cloud communication technologies are necessary for the development of an IoT-based smart energy meter. Microcontrollers, such as the ESP32 and ESP8266, which have integrated Wi-Fi, low power consumption, and sufficient computational capacity for continuous data sampling, are commonly used in such systems. While current measurements are performed using Hall-effect sensors, such as the ACS712, which enable precise RMS calculations, voltage sensing is often performed using modules such as ZMPT101B. Cloud services, such as Firebase, ThingSpeak, and Blynk, are crucial for data storage, visualization, remote monitoring, and real-time alerts. When combined, these elements offer the fundamental infrastructure required to establish a scalable and effective energy monitoring system.

Considerations

Several crucial factors that impact performance and dependability must be considered when designing an IoT-based energy monitoring system. Latency is important because it can affect user response and real-time monitoring owing to data transmission delays. Sensor accuracy is equally crucial, as it requires an exact calibration to provide reliable readings of voltage, current, and power. Cost efficiency must also be considered, especially for consumer-grade applications or large-scale deployments that require the utilization of reasonably priced yet dependable components. Security is also a major concern, as data on energy use that is transmitted over the internet might be tampered with or accessed by unauthorized parties. System integrity depends on safe user identification, encrypted data transport, and secure communication protocols.

PROPOSED SYSTEM ARCHITECTURE

Architecture

The system comprises sensors linked to a microcontroller that uploads data to a cloud server after processing it in real time. A dashboard on a web or mobile device allows users to access the data. The multilayer system architecture of the IoT-based smart energy meter enables precise sensing, effective processing, and smooth transfer of energy consumption data. The sensing layer, which is at the base, comprises voltage and current sensors that measure the electrical characteristics of the load in real time. The processing layer, which is based on a microcontroller, such as ESP32 or Arduino, receives analog signals from these sensors, digitizes the input values, calculates the voltage, current, power, and energy, and prepares the data for communication. To provide a dependable connection between the meter and remote servers, the communication layer incorporates wireless modules, such as Wi-Fi, GSM, or LoRa. This layer guarantees continuous, safe, and low-latency data transport to cloud platforms. IoT dashboards, analytics tools, and databases are used to store, analyze, and display data in the cloud/server layer, which serves as a central repository. The last tier, the user interface tier,

provides customers and utility companies with real-time access to use data via online dashboards or mobile applications, allowing them to track consumption, receive warnings, and make informed energy decisions. These interconnected layers work together to provide a robust, scalable, and intelligent architecture that facilitates automatic data management, real-time monitoring, and interaction with smart grid systems.

Methodology

From hardware design to real-time data display, the proposed IoT-based smart energy meter methodology adopts a methodical approach. To monitor electrical characteristics precisely, a microcontroller unit (Arduino/ESP32) is coupled with key sensing components, such as a voltage sensor and a current sensor (ACS712/CT sensor). Real-time power consumption calculations are performed by the microcontroller after processing the detected data. The system is then interfaced with an IoT communication module, usually Wi-Fi or GSM, to securely transmit the processed data to a cloud server or IoT platform, such as Things Speak, Firebase, or MQTT-based services. Through dashboards that are accessible to users, the cloud platform saves, evaluates, and displays the data. To improve monitoring effectiveness, the system also incorporates software algorithms for anomaly identification, threshold-based alerts, and recurring data logging (Figure 2). A web or smartphone application is created to provide historical patterns, alarms, and real-time usage. Testing and validation were conducted by comparing the measured values with conventional meters and assessing network performance under various load scenarios. The accuracy, responsiveness, and applicability of the system for real time

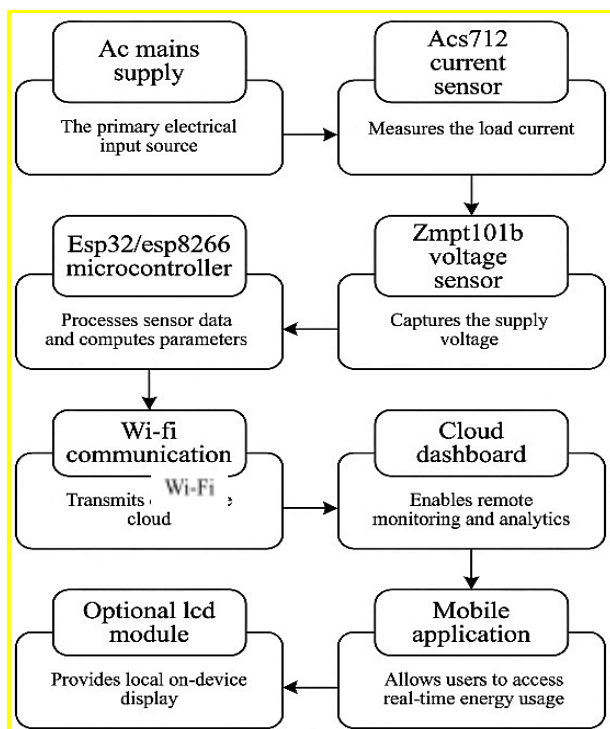


Figure 1. Architecture of a smart energy meter.

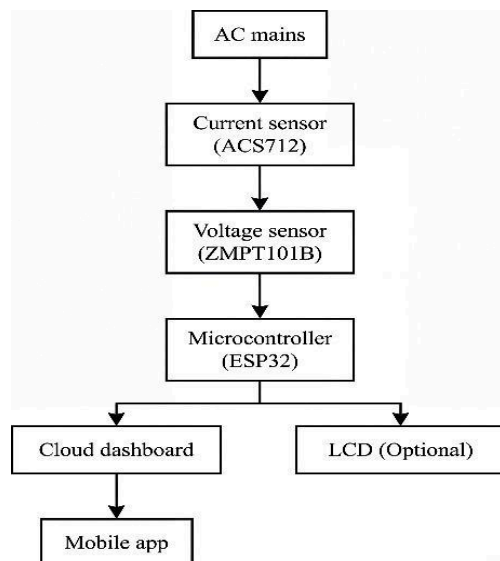


Figure 2. Block diagram of a smart energy meter.

Mitigation of Identified Problems

By combining real-time sensing, cloud connectivity, and automatic alarm mechanisms, the proposed IoT-based smart energy meter successfully addresses the main issues in conventional monitoring systems. Instant energy use notifications lower the risk of overloads or unexpected charges by assisting users in promptly identifying aberrant consumption patterns. Remote monitoring improves transparency and decision-making by providing customers and utility companies with access to precise, current energy data from any location. Additionally, the cloud-based recording system guarantees a transparent and unchangeable view of consumption patterns, and the use of accurate voltage and current sensors improves measurement accuracy. When combined, these characteristics offer a more dependable, effective, and user-focused approach to overcoming the drawbacks of traditional energy metering.

HARDWARE IMPLEMENTATION

Hardware Components

1. *ESP8266/ESP32*: The system's core processing unit is the ESP8266/ESP32 microcontroller, which has high computing power, low power consumption, and an integrated Wi-Fi connection. For monitoring and analysis, it collects sensor data, interprets it, and sends real-time energy data to the cloud platform.
2. *ACS712 current sensor*: The ACS712, a Hall-effect-based current sensor, provides accurate and isolated AC/DC measurements. Its high sensitivity and built-in signal conditioning make it ideal for monitoring household current flow, ensuring precise power calculation, and enhancing system safety.
3. *ZMPT101B voltage sensor*: Excellent linearity and precision are achieved when measuring AC voltage with the ZMPT101B voltage sensor. It is particularly designed for low-voltage signal output, enabling a secure microcontroller interface while preserving accurate real-time voltage measurements.
4. *Power supply module*: All system components are guaranteed a steady and controlled voltage thanks to the power supply module. It ensures electrical safety and continuous functioning of the complete smart energy meter by converting AC mains to the necessary DC levels required by the microcontroller and sensors.

SAMPLE CALCULATIONS

To validate the performance and accuracy of the proposed IoT-based smart energy meter, sample electrical parameter calculations were performed using the measured values obtained from the

ACS712 current sensor and ZMPT101B voltage sensor. The following readings were recorded:

- Measured voltage (V_{rms}) = 229.5 V
- Measured current (I_{rms}) = 2.14 A
- Power factor (pf) = 0.92
- Duration of load operation (t) = 3 hours

Summary Table Kindly Remove This

Table 1. Summary of calculated electrical parameters.

Parameter	Value
Voltage	229.5 V
Current	2.14 A
Power factor	0.92
Real power	452.6 W
Apparent power	491.1 VA
Reactive power	191.9 VAR
Energy (3 hours)	1.357 kWh

Real Power Calculation

Real or active power is computed using:

$$P = V_{rms} \times I_{rms} \times pf$$

$$P = 229.5 \times 2.14 \times 0.92 = 452.6 \text{ W}$$

Apparent Power

$$S = V_{rms} \times I_{rms}$$

$$S = 229.5 \times 2.14 = 491.1 \text{ VA}$$

Reactive Power

Reactive power is calculated from:

$$Q = \sqrt{S^2 - P^2}$$

$$Q = \sqrt{491.1^2 - 452.6^2} = 191.9 \text{ VAR}$$

Energy Consumption

Energy consumed over a period of time t :

$$E = P \times t$$

$$E = 452.6 \times 3 = 1357.8 \text{ Wh} = 1.357 \text{ kWh (from Table 1)}$$

RESULTS AND DISCUSSION

The system offers extremely precise real-time measurements of voltage, current, and power consumption, with little deviation from conventional reference instruments, according to the experimental evaluation of the proposed IoT-based smart energy meter. Energy use patterns may be continuously tracked and shown thanks to the cloud platform's robust data transfer. When abnormal consumption occurs, the alarm mechanism reacts quickly, and the real-time dashboard successfully displays instantaneous load fluctuations. Additionally, the ESP8266/ESP32 guarantees effective data processing with minimal latency, and the incorporation of calibrated sensors reduces measurement errors. Overall, the findings demonstrate that, in comparison with conventional metering systems, the proposed system provides dependable performance, increased monitoring capabilities, and greater transparency.

CONCLUSION

The proposed IoT-based smart energy meter effectively illustrates a dependable and effective method for tracking power usage in homes and businesses in real time. The system overcomes the main drawbacks of conventional energy meters, such as delayed readings, lack of transparency, and limited user input, by combining precise sensor modules, a Wi-Fi-enabled microcontroller, and cloud-based data display. The system operates with high precision, low latency, and consistent data transfer, providing consumers with instant insights into their energy consumption habits, according to the experimental results. Overall, the adopted approach boosts monitoring capabilities, promotes energy awareness, and builds a platform for smarter and more sustainable power management.

Future Scope

Future iterations of the smart energy meter may incorporate sophisticated analytics, such as defect prediction, anomaly identification, and load forecasting, based on machine learning. Higher-capacity sensors and more reliable communication protocols, such as LoRaWAN or 5G, may be added to the system to provide multiphase and industrial-grade monitoring. Its usefulness might be further improved by adding demand response systems, automated household appliance control, and prepaid billing. Transparency, dependability, and user engagement will also be enhanced by adopting blockchain-based energy data security and mobile application support. These developments have the potential to transform the system into an all-inclusive smart energy management platform for extensive smart grid and smart home applications.

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